

RADIO SCIENCE SYSTEM DESIGN and MEASUREMENT RESULTS for the NASA DEEP SPACE NETWORK (DSN)

Remi C. LaBelle^a

^aJet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA,

remi.labelle@jpl.nasa.gov

Abstract

Radio science measurements have been performed using the NASA Deep Space Network (DSN) with many different spacecraft over several decades. Radio science has been used for the study of planetary atmospheres, the solar corona and the search for gravity waves, among other things. The majority of these measurements are made using the X and Ka-band deep space bands. Although the primary mission for the DSN is tracking, telemetry and command (TT&C) for NASA's many deep-space spacecraft, radio science measurements continue to be an important secondary mission. The science requirements for these measurements have resulted in stringent performance requirements for both the spacecraft and ground system equipment. In particular, the requirements for amplitude stability, phase stability (Allen deviation) and phase noise are very demanding. The system Allen deviation requirement at Ka-band is $< 2.4 \text{ E-15}$ over 1000 seconds, while the phase noise requirement is $< -50 \text{ dBc/Hz}$ for a 1 Hz offset. Various design techniques have been used for the DSN radio frequency (RF) electronics, high power transmitters and antenna structures to meet the stringent requirements for all 3 of these parameters. Some details for the design techniques will be described in the paper. Another important consideration for a radio science system is the verification approach for components, as well as for individual subsystems and then the overall system. Phase-locked oscillators (PLOs) are one of the key component types that determine overall phase noise and Allen deviation system performance. Measurement techniques used for PLOs, as well as for the overall ground system, will be discussed. Measurement results for the 2 new DSN antennas, recently built under the DSN Aperture Enhancement Project (DAEP) will also be shown. In addition, some recent radio science measurements from the Cassini and JUNO missions, using the new antennas, will be presented.

Keywords: Radio science, Deep space communication equipment, beam waveguide antenna, Allan deviation measurements, Phase-locked oscillators

1. Introduction

Radios science experiments involve measurements of small changes in phase, frequency, amplitude and/or polarization of the radio signal propagation from an interplanetary spacecraft to an Earth receiving station. By properly analyzing the radio metric data, investigators can infer characteristic properties of the atmospheres, ionospheres, and rings of planets and satellites. They can also measure gravitational fields and ephemerides of planets, monitor the solar plasma and

magnetic fields activities, and test aspects of the theory of general relativity.

Although the primary mission for the DSN is tracking, telemetry and command (TT&C) for NASA's many deep-space spacecraft, radio science measurements continue to be an important secondary mission. The fundamental science requirements for these measurements have resulted in stringent performance requirements for both the spacecraft and ground system equipment. In particular, the radio science requirements were a key driver in the design of the new beam waveguide (BWG) antennas currently being built under the DSN Aperture that are

Enhancement Project (DAEP), for which the initial test and calibration results were previously reported [1]. The basic structure of the DSN BWG antennas, as shown in Fig. 1 and Fig. 2, with all of the electronics in a pedestal room underground, is designed for highly stable thermal conditions and therefore good phase and amplitude stability.

This paper will focus on the requirements that were flowed down to the microwave and TT&C subsystems of the ground station equipment and the design and measurement techniques that were used to meet those requirements and verify performance. In particular, a simplified way of specifying long-term phase stability was used for defining oscillator requirements. This enabled a lower cost approach for component and subassembly testing by commercial suppliers who do not have elaborate Allan deviation test setups available.

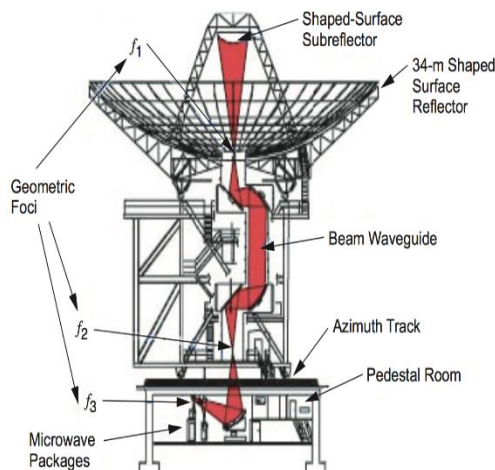


Fig. 1. A diagram of a DSN 34-meter BWG antenna, indicating the three foci at F1, F2 and F3.



Fig. 2 The DSS-35 antenna in Canberra

2. Radio Science Mission Requirements

The use of interplanetary spacecraft signals for radio science measurements dates back to the early days of NASA and JPL, starting with the Mariner missions in the 1960s [2]. Initially, the science information was extracted from Doppler and range data generated by the tracking system. Later, spacecraft radio science was expanded to comprise two broad categories of investigation [3]:

1. Occultation measurements of the radio signal as it passes through and probes the media of interest (atmosphere, rings, etc.) while the spacecraft is on the far side of the planet.
2. Tracking measurements wherein the perturbations of the spacecraft orbit are analyzed for information on gravity or other effects.

There are five basic signal characteristics that are used to extract science information from a spacecraft signal and these are described in the following section along with the physical characteristics they are used to study [4].

2.1 Phase delay

- mass and mass distribution of planets and satellites
- planetary spin characteristics
- planetary size, shape and gravity field
- gravitational waves
- pressure, temperature and density of atmospheres
- electron concentration of ionospheres and interplanetary plasma

2.2 Spectrum

- Atmospheric turbulence
- Turbulence of solar wind
- Distribution of planetary surface slopes
- Size and velocity distribution of ring particles

2.3 Group delay

- *electron concentration of ionospheres and interplanetary plasma*
- *solar corona shape, density and large-scale flow patterns in solar wind*
- *parameters of general relativity*

2.4 Amplitude

- *pressure, temperature and density profiles of atmospheres*
- *location, density and composition of clouds*
- *size of planetary ring particles*

2.5 Polarization

- *Shape of planetary ring particles*
- *Electron density and magnetic field in ionospheres and the solar corona*
- *Dielectric properties of planetary surfaces*
- *Test of the weak equivalence principle*

A pictorial of a group delay measurement scenario to study general relativity with the Cassini spacecraft is shown in Fig. 3. In this example, bending of the spacecraft signal is observed during solar conjunction. A Mars atmosphere occultation experiment with Mars Global Surveyor (MGS) is shown in Fig. 4. A typical example of the use of a spacecraft signal spectrum for radio science was the Voyager 1 flyby of Saturn [5]. The geometry of a ring occultation is shown in Fig. 5 and the received X-band spectrum for the spacecraft behind Ring A is shown in Fig. 6. The broadening of the spectrum is from ring particle scattering. In this example, the phase noise floor of the measurement system (both spacecraft and ground system) needs to be below the level of the science information (spectrum due to the ring particles).

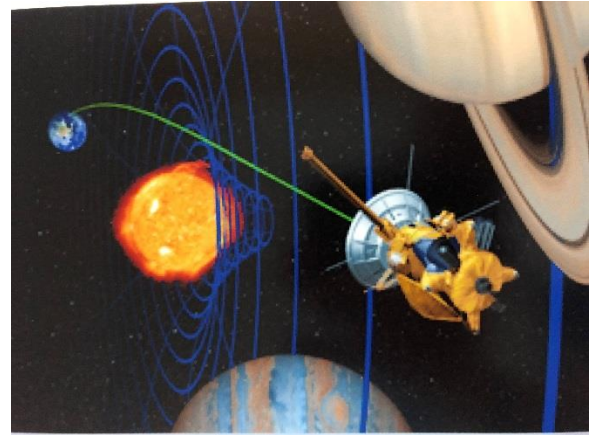


Fig. 3. General relativity experiment with Cassini

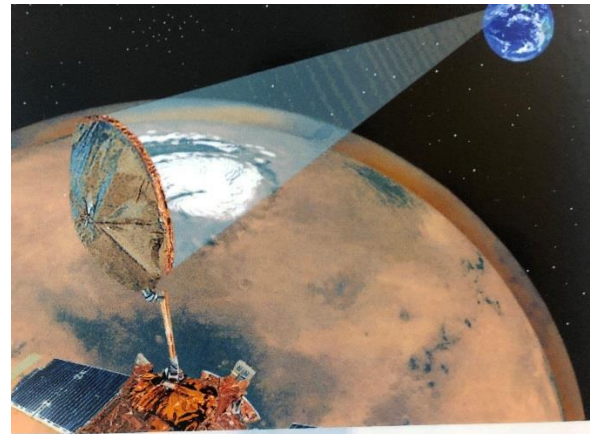


Fig. 4. Mars atmosphere occultation with Mars Global Surveyor

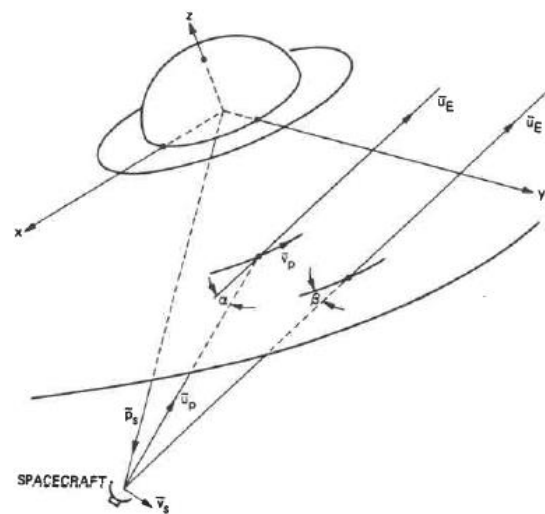


Fig. 5. Geometry of ring occultation: signal on direct and indirect path to Earth.

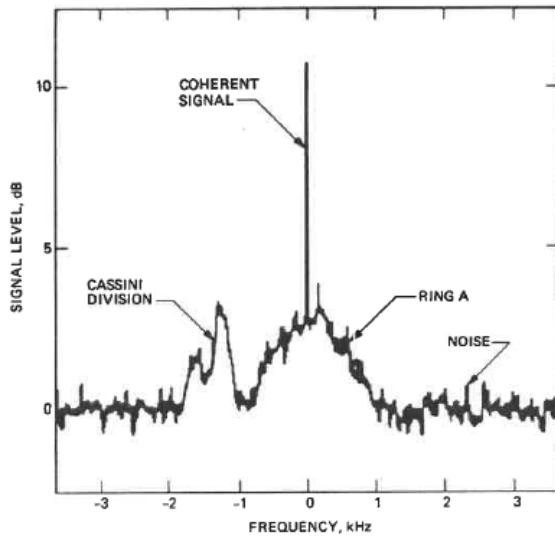


Fig. 6 Spectrum of received signal when Voyager 1 was behind Saturn's Ring A.

3. DSN System and Subsystem Requirements

3.1 System requirements

From the science parameters previously outlined, it is apparent that phase noise and phase stability, or Allan deviation, are two of the key requirements for the radio science system. The system is composed of both the spacecraft and the DSN ground system. The general approach for requirements allocation to the DSN is to insure that the DSN is a small contributor to the overall system, i.e. maintain a phase noise and Allan deviation performance significantly lower than the spacecraft. The DSN system requirements are summarized in Table 1, for phase noise, and Table 2 for Allan deviation. The requirements are separated into uplink and downlink for the 3 different bands (S, X and Ka) that are used in the DSN. This provides a criteria for the uplink and downlink subsystems when they are tested separately. In addition, some radio science measurements are done non-coherently, using the downlink only, e.g. the occultation measurements. The combined uplink/downlink system requirements can be obtained by using the root-sum-square (RSS) combination of the separate requirements.

RS - Phase Noise Requirements -dBc/Hz					
Band	Offset	1Hz	10Hz	100Hz	10kHz
S	UP	-65	-75	-78	-78
X	UP	-54	-65	-74	-74
Ka	UP	-42	-53	-64	-64
S	Down	-65	-75	-78	-78
X	Down	-63	-69	-70	-70
Ka	Down	-50	-55	-57	-65

Table 1 DSN system phase noise requirements (S, X, Ka-band)

RS - Allan Deviation Requirements					
Band	Int time	1sec	10 sec	100sec	1000sec
S	UP	1.0E-12	1.0E-13	4.4E-14	4.4E-15
X	UP	1.1E-12	1.1E-13	4.4E-14	4.4E-15
Ka	UP	NA	NA	1.8E-15	1.8E-15
S	Down	4.5E-13	8.2E-14	9.1E-15	5.3E-15
X	Down	1.0E-12	1.0E-13	3.6E-14	5.9E-15
Ka	Down	7.0E-13	1.0E-13	3.3E-14	2.4E-15

Table 2 DSN system Allan deviation requirements (S, X, Ka-band)

Two other key DSN system (uplink/downlink) requirements that are derived from the science requirements are as follows:

Amplitude stability: 0.25 dB over 30 minutes, 0.5 dB over 8 hours

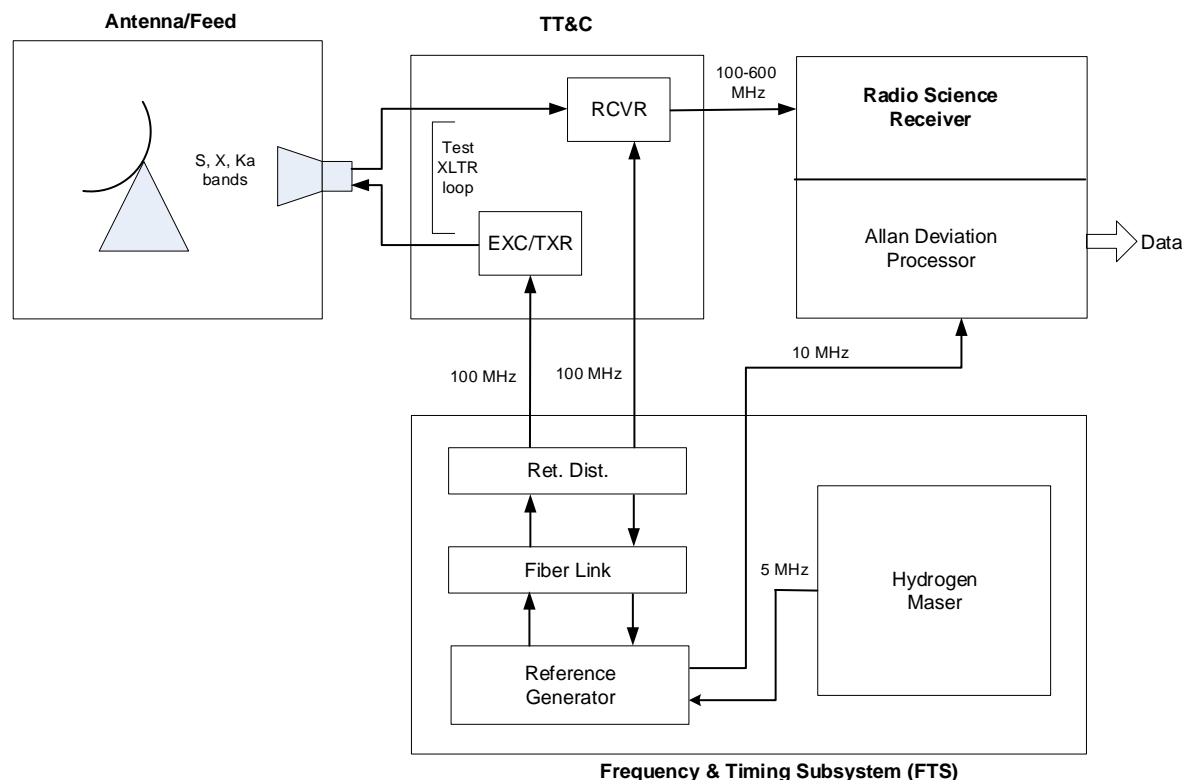
Polarization isolation: > 25 dB

3.2 Subsystem requirements

Historically, the DSN radio science system has been divided into 4 different subsystems, which are the Antenna & Feed, Tracking Telemetry and Control (TT&C), Frequency and Timing Subsystem (FTS) and the Radio Science (RS) Receiver. The

interconnection of these 4 subsystems is shown in Fig. 7. Allocation of the phase noise and Allan deviation requirements to these subsystems is partly based on their realizable performance, and is shown in Table 3 and Table 4. For the system phase noise, the FTS subsystem is the main contributor, and the other subsystems are specified to add only a small

contribution. Since the frequency references in the TT&C and RS subsystems are derived from, and coherent with, the FTS references, their phase noise allocations are for residual noise. For the Allan deviation performance, the FTS and antenna/feed subsystems are the main contributors.



Remi LaBelle
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Fig. 7 Radio Science system block diagram

RS - Phase Noise Allocations – XKa dBc/Hz					
Subsys	Offset	1Hz	10Hz	100Hz	10kHz
FTS		-58	-68	-70	-70
RS Rcvr		-75	-85	-85	-85
Ant/feed		-70	-75	-75	-75
TT&C		-60	-70	-80	-86
Total	Up/Down	-55	-65	-68	-68

Table 3 Allocation of phase noise requirements (XKa-band)

RS - Allan Deviation Allocations - Ka					
Subsystem	Int time	1sec	10 sec	100sec	1000s
FTS		2.0E-13	4.0E-14	1.5E-15	1.5E-15
RS Rcvr		1.1E-14	4.7E-15	5.0E-16	4.4E-16
Ant/feed		3.0E-13	3.0E-14	1.4E-15	1.4E-15
TT&C		1.1E-14	4.7E-15	5.0E-16	5.5E-16
Total	Up/Down	3.6E-13	3.1E-14	2.2E-15	2.1E-15

Table 4 Allocation of Allan deviation requirements (Ka-band)

3.3 Phase-locked oscillator requirements

The main contributors to both phase noise and Allan deviation performance of the TT&C subsystem are the phase-locked oscillators PLOs. These PLOs are used for upconversions and downconversions as well as for the high speed clocks in the digital subsystems. The locations of the various PLOs are shown in Fig. 8 and Fig.

9. These PLOs are obtained from vendors who usually do not have equipment to measure Allan deviation. Therefore, a conversion to phase vs temperature was derived, based on an estimate for the temperature variation vs time in the operational environment.

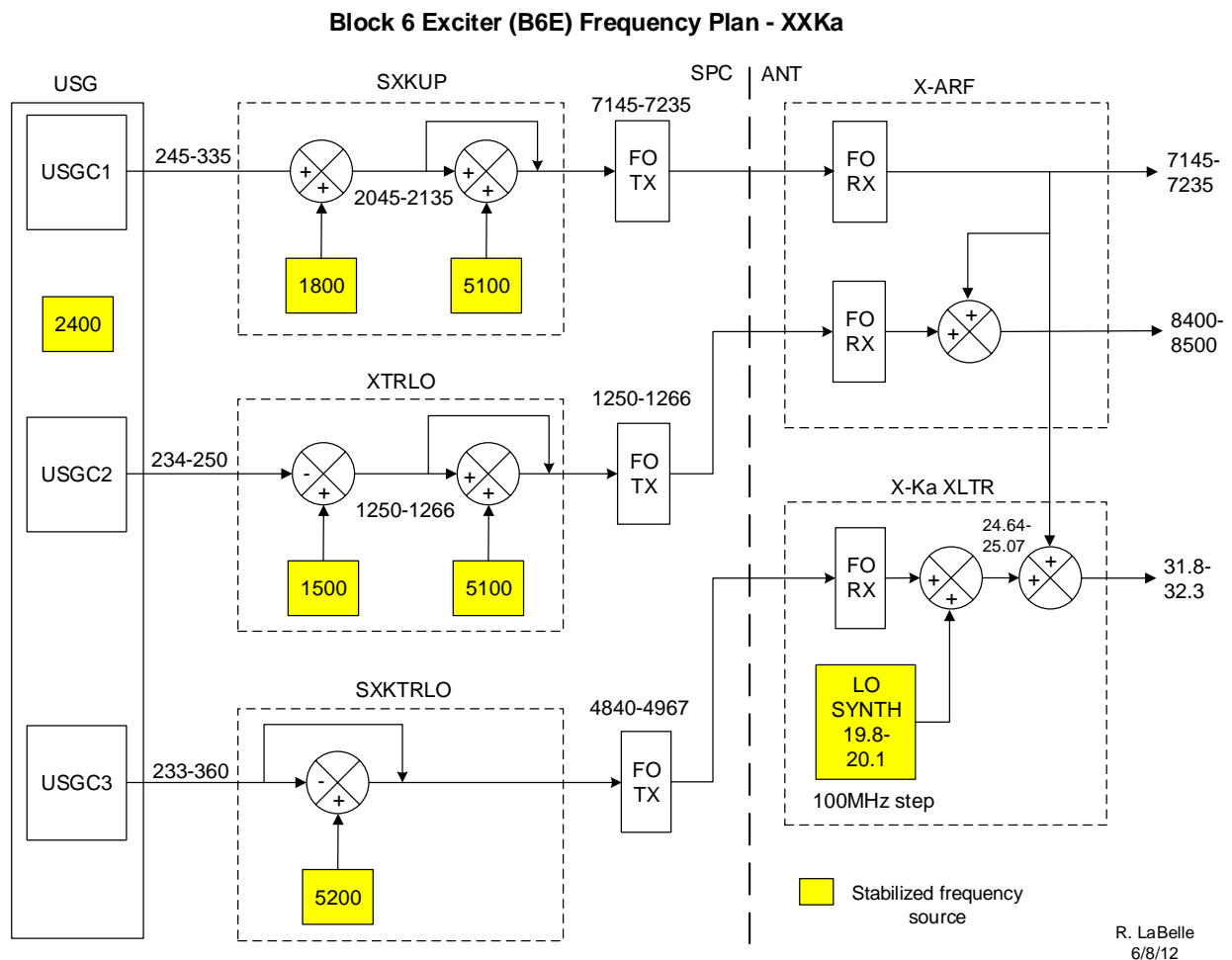


Fig. 8 Stabilized oscillators in the uplink electronics

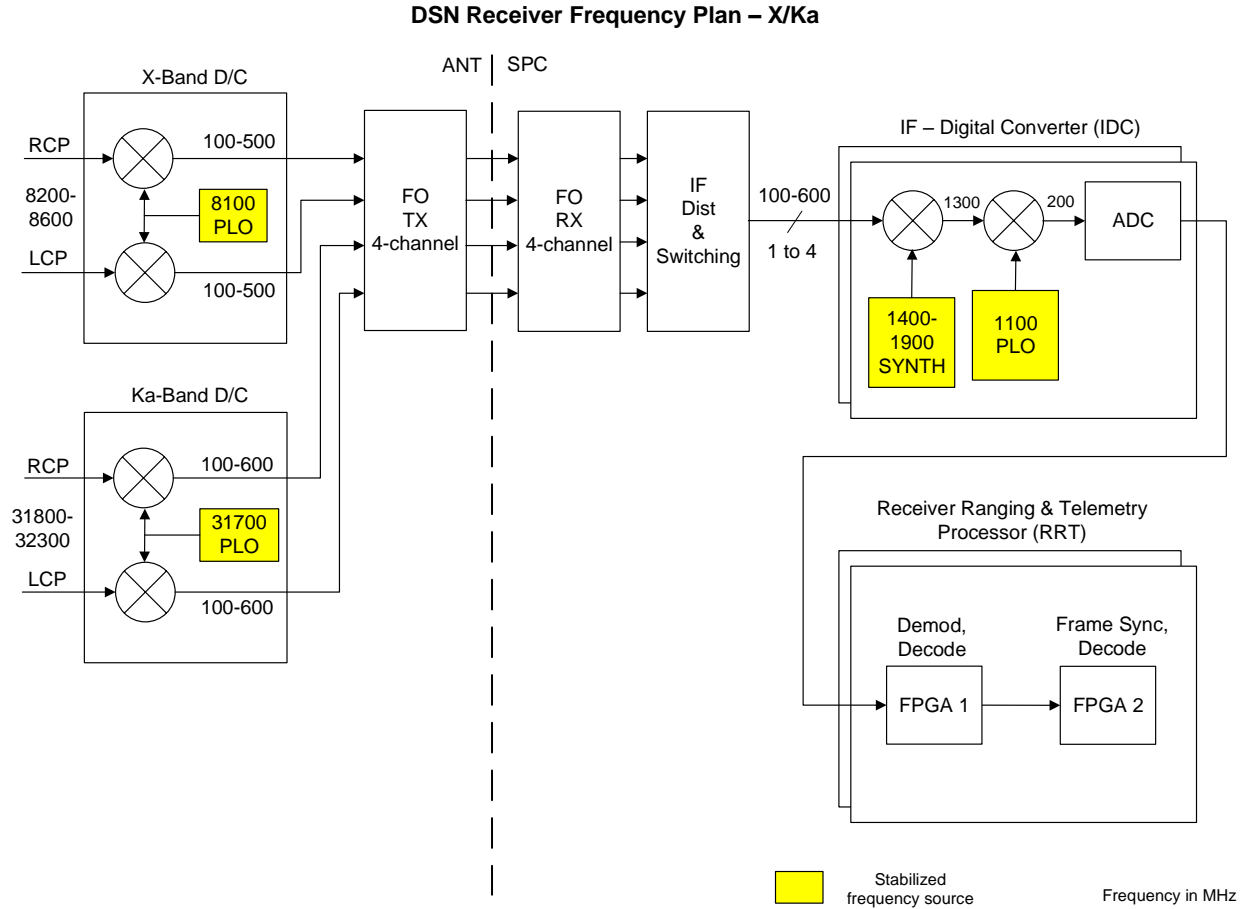


Fig. 9 Stabilized oscillators in the downlink electronics

The conversion to phase vs temperature was derived as follows:

$\dot{\sigma}_T(\mathbb{T})$ = standard deviation of temperature variation for integration time, \mathbb{T} (i.e. RMS temp. variation)

ρ = temp. coeff. of phase for DUT (deg/°C)

$\dot{\sigma}_f(\mathbb{T})$ = fractional frequency deviation or Allan deviation

Approach: estimate $\dot{\sigma}_f(\mathbb{T})$ for a frequency source or component from its ρ and the temperature variation, $\dot{\sigma}_T(\mathbb{T})$

$$\dot{\sigma}_f(\mathbb{T}) = \frac{\Delta f(\mathbb{T})}{f_0} = \frac{d\Delta\phi(\mathbb{T})}{f_0 dt \cdot 360} \quad (1)$$

$$\text{now let } \Delta\phi(\mathbb{T}) = \rho \cdot \dot{\sigma}_T(\mathbb{T}) \quad (2)$$

$$\text{and } \frac{d\Delta\phi(\mathbb{T})}{dt \cdot 360\mathbb{T}} = \rho \cdot \frac{\dot{\sigma}_T(\mathbb{T})}{360\mathbb{T}} \quad (3)$$

$$\text{therefore } \dot{\sigma}_f(\mathbb{T}) = \frac{\rho \cdot \dot{\sigma}_T(\mathbb{T})}{f_0 \mathbb{T} \cdot 360} \quad (4)$$

The resulting phase sensitivity requirements for the uplink and downlink subsystems are summarized in Table 5, assuming that $\dot{\sigma}_T(\mathbb{T}) = 0.3$ C and $\mathbb{T} = 1000$ sec.

Table 5 Phase sensitivity for TT&C assemblies

Assembly	Freq (MHz)	Raw Ph. sens (deg /deg)	Oven gain	Net Phase sens (deg /deg)	Calc All. Dev. (1000 s)	All. Dev. Rqmt (1000 s)
Receiver:						
X-band D/C	8400	10	40	0.25	2.5E-17	2.0E-16
KA-Band D/C	32000	200	40	5	1.3E-16	2.0E-16
Exciter:						
USG-PLO	2400	20	40	0.5	1.7E-16	2.0E-16
SX U/C	7190	40	40	1	1.2E-16	2.0E-16
FO Link	7190	1	1	1	1.2E-16	3.0E-16
X-Ka XLTR	32000	200	40	5	1.3E-16	2.0E-16

4. Design for Low Noise and High Stability

Several design upgrades for the new 34 meter antennas in the DSN were done during the on-going DAEP project. An overview of the electronics upgrades, including improvements for Radio Science, was previously reported [6]. Some additional details on design considerations specifically for improved phase noise and phase stability are summarized below.

4.1 Antenna/feed subsystem

Phase delay variations can be caused by physical path variations within the antenna due to temperature, gravity and wind effects. In fact, analysis has shown that, for the antenna, the dominant contributor to the system Allan deviation is mechanical deformation due to wind. As a result, the whole support structure for the 34-meter BWG antennas is designed to be extremely rigid.

4.2 FTS subsystem with fiber optic cables

The hydrogen maser frequency standard is the main contributor to the system performance for both phase noise and Allan deviation. The maser is used in the DSN for its superior stability at 1000 second integration times, as compared to Cesium or Rubidium standards. Transporting the frequency references from the maser to the equipment in the antenna is also critical to maintaining good phase stability. This is especially true at the Goldstone DSN complex where the BWG cluster of antennas is 16 km from the control room. This is done using

stabilized fiber optic links, with a return fiber carrying 100 MHz for feedback phase control of the link [7]. The fiber used for most antennas has a “standard” temperature coefficient of 7 ppm/deg C but the fibers are buried at least 6 feet underground for good thermal stability.

4.3 TT&C subsystem

Transmitter: The major contributor of phase instability in the 20 kW and 80 kW transmitters is water temperature variations in the cooling system. Therefore, a temperature control loop with adequate gain is used to maintain the water temperature within +/- 1 deg C. With this level of temperature stability, the transmitter is only a small contributor to the overall TT&C subsystem.

Receiver/Exciter: As mentioned previously, the main contributors to both phase noise and Allan deviation in the TT&C subsystem are the phase-locked oscillators. In order to meet the phase noise requirements out to 10 KHz offsets, the loop bandwidths are typically set to > 10KHz so that the total phase noise from the PLO is just 20logN of the 100 MHz reference noise. The Allan deviation of the PLOs is determined by either thermal control or digital phase vs temperature compensation. In either case, the net phase vs temperature sensitivity is reduced to < 5 deg. Phase /deg C (for Ka band). The net temperature sensitivity for the major assemblies in TT&C is shown in Table 5.

5. Measurement Techniques and Results

5.1 Subsystem testing

The TT&C assemblies (upconverters, downconverters) are tested separately at the manufacturer prior to integration at JPL into the larger subsystems. As mentioned earlier, the PLOs and/or converter assemblies are verified to meet the phase vs temperature requirements, in order to project what the subsystem Allan deviation performance will be. For phase noise characterization, the PLOs are measured in a “pair” configuration, to determine their residual phase noise contribution. With this approach, 2 oscillators of the same design are mixed together and the DC or baseband output is the combined phase noise. The phase noise for one oscillator is then the total minus 3 dB. Typical measurements for a 20 GHz PLO are

shown in Fig. 10 (for phase vs temperature) and Fig. 11 (for residual phase noise).

For the FTS subsystem, measurements are made after installation at the DSN complex, so that the combined performance of the hydrogen maser, reference generator, distribution assembly and fiber optic link are included. A typical result from a new 34-meter antenna in Canberra (DSS-35) is shown in Fig. 12.

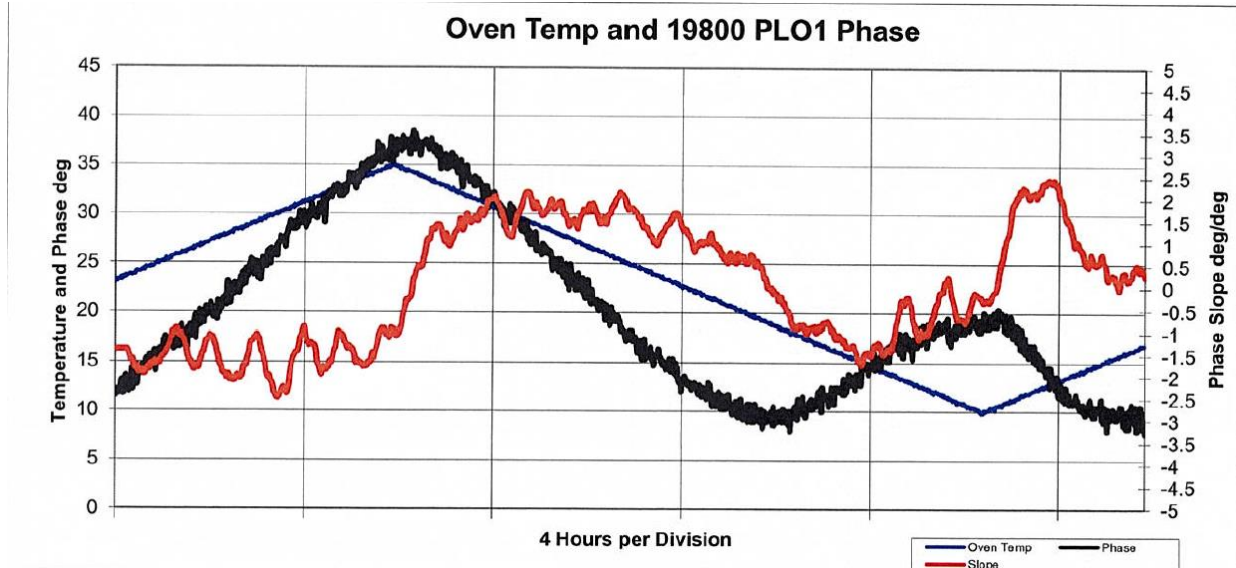


Fig. 10 Phase vs temperature measurement for 19.8 GHz oscillator

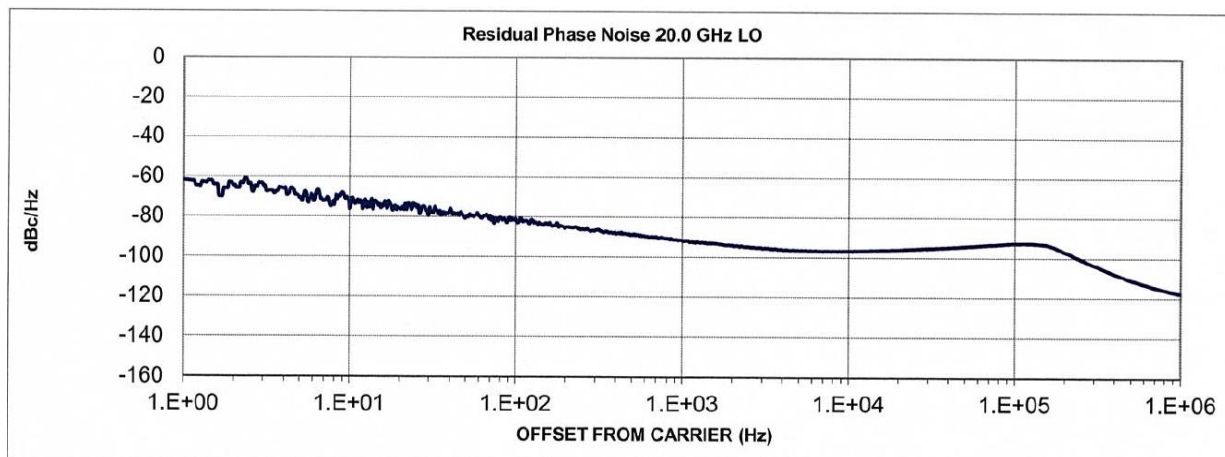


Fig. 11 Residual phase noise measurement for 20 GHz oscillator

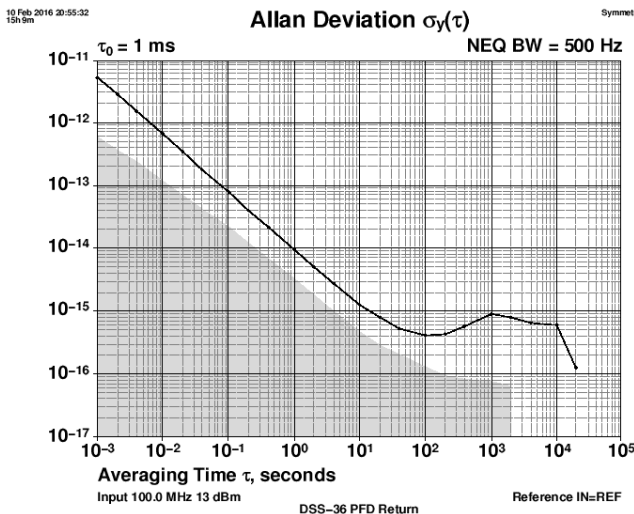


Fig. 12 Allan deviation for the optical 100 MHz distribution (PFD)

5.2 System testing

System Performance Tests (SPTs) are performed during commissioning of a new antenna. In addition ,phase noise and stability tests are performed at least once per year at all frequency bands (S, X and Ka) to verify consistent performance. These measurements are typically done with the combined uplink and downlink, using the test translator turn-around loop shown in Fig. 7. The result is then the upper bound for both the receiver and exciter/transmitter subsystems. Typical results for the newest BWG antenna in Canberra (DSS-36) are shown in Fig. 13 and Fig. 14.

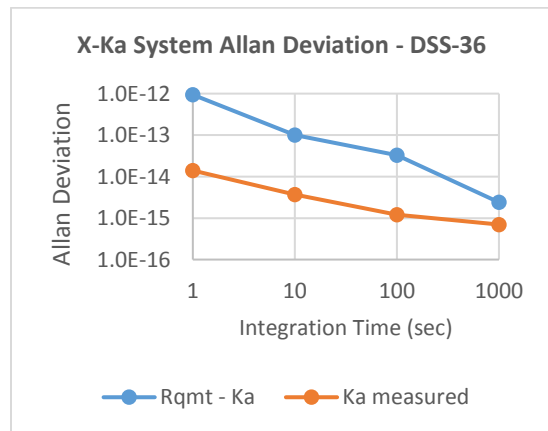


Fig. 13 Measured system Allan deviation (X-Ka)

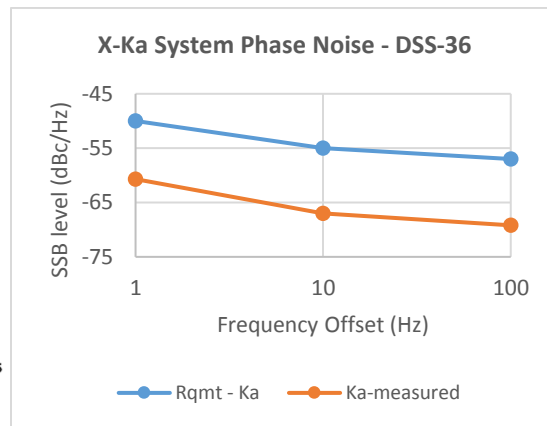


Fig. 14 Measured system phase noise (X-Ka)

6. Recent DSN Radio Science Results

One of the most prolific recent producers of radio science measurements was the Cassini mission, until its “Grand Finale” mission end in September, 2017. As part of the on-going studies of Saturn’s rings, the ring rhythm was discovered by Cassini, as shown in Fig. 15. Another mission that continues to provide radio science measurements is JUNO, in orbit around Jupiter (shown in an artist’s conception in Fig. 16). This mission is planned to continue until at least 2021.

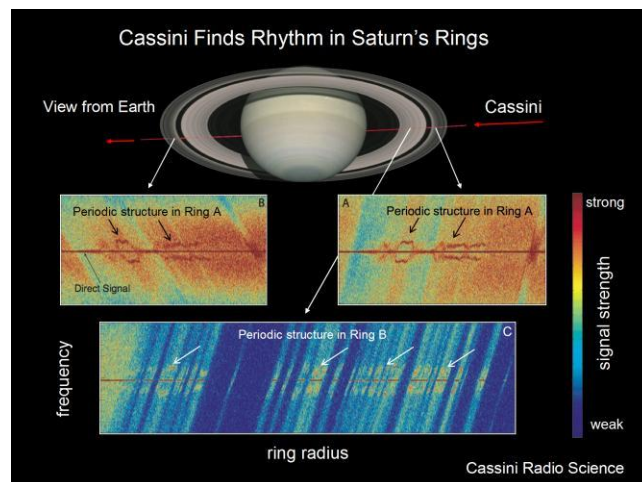


Fig. 15 Saturn’s ring rhythm from Cassini radio science

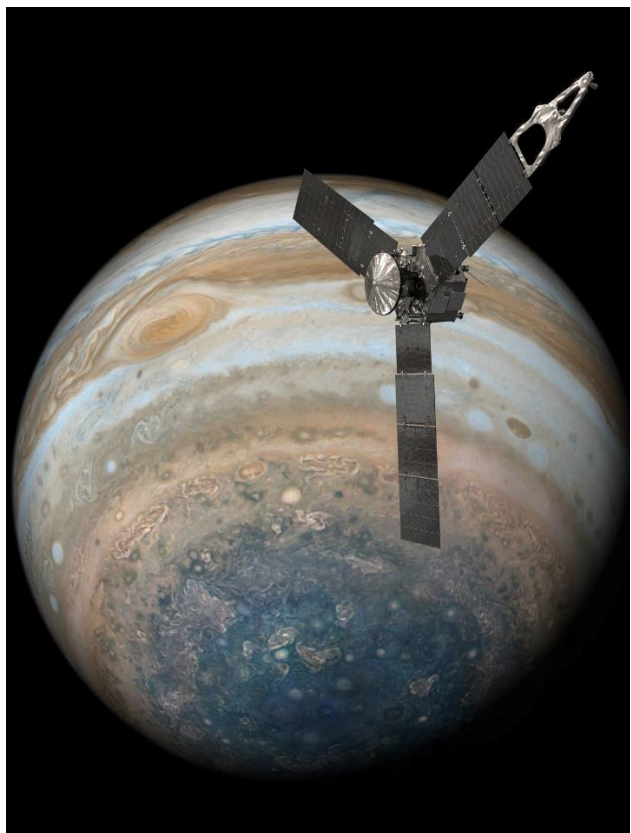


Fig. 16 JUNO orbiter at Jupiter

Conclusion

Radio science measurements have been a significant part of the DSN tracking activities since its inception in the early 1960s. In fact, nearly all of the NASA solar and planetary flyby and orbital missions have used their downlink signals for some type of radio science. Due to the stringent requirements for amplitude and phase, radio science has also been a significant driver for the electrical and mechanical design of the different DSN subsystems. With the six new DSN 34-meter antennas being built under the DAEP project, the system performance has some margin for additional improvements in radio science data. In addition, some planned improvements to both the DSN and spacecraft subsystems will further improve the overall radio science sensitivities. The new open loop receivers for the DSN will be brought on-line in 2019, with a much higher sampling rate (3.2 GHz) which will greatly reduce the spectrum processing time. Although there is currently one DSN antenna (DSS25 at Goldstone) that has a Ka-band uplink, a

new task will add a Ka uplink to one antenna at each complex. This will greatly increase the radio science data returns for spacecraft such as JUNO that have a Ka-Ka transponder.

On the spacecraft side, a new concept for the on-board clocks will be demonstrated by the Deep Space Atomic Clock (DSAC), a JPL experiment to be hosted on the Orbital Test Bed spacecraft. While primarily intended to improve navigation, the enhanced stability of the DSAC technology is expected to improve the resolution of one-way radio science as well. One of the JPL flagship missions currently under development, Europa Clipper, is expected to provide a wealth of radio science data from the Jovian system, and the moon, Europa, in particular. The Psyche mission to the asteroid of the same name, planned for launch in 2022, will have a gravity science experiment. Finally, a new development is currently being done to implement Deep Space Optical Communications (DSOC) in the DSN within the next several years. Although this new technology is intended primarily for high data rate communications from deep space, there will undoubtedly be radio science applications for DSOC as well.

Acknowledgement

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